Muon Cooling Design Status

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APS Meeting, Muon Collider Symposium (Virtual)
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Outline

- Muon Collider overview
- Ionization cooling
  - Basic theory
  - Application to a Muon Collider
  - Simulation results
- Future directions
- Summary

Muon Collider parameters

- Parameters as developed by the MAP effort:

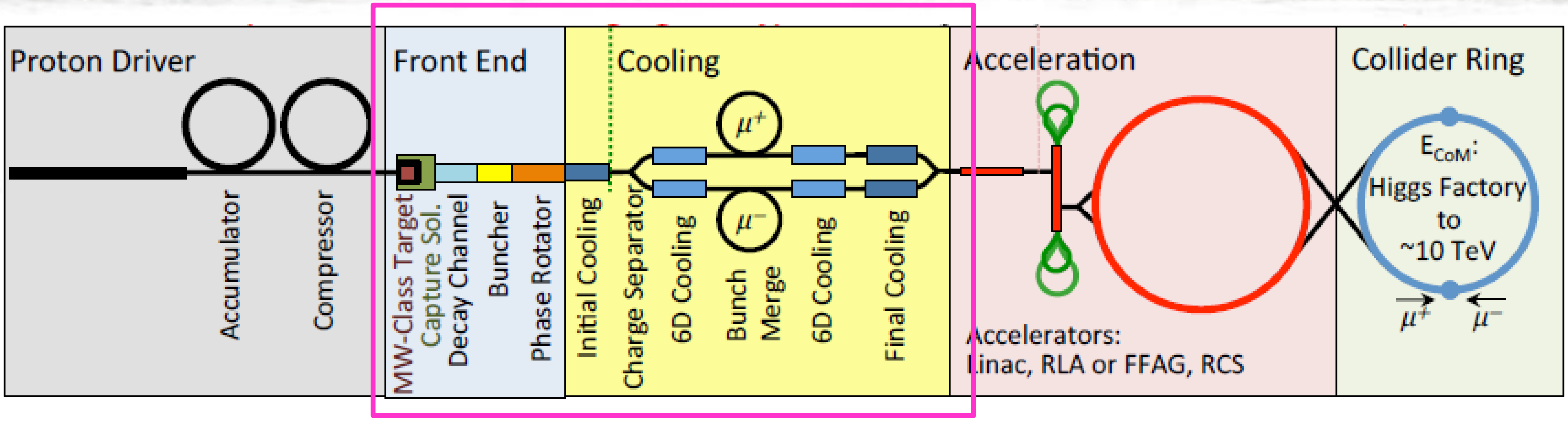
$$\mathcal{L} = \frac{f_{col} \cdot n_{\mu_+} \cdot n_{\mu_-} \cdot \beta \cdot \gamma}{4\pi\left(\varepsilon_{x,n} \cdot \beta_x^*\right)^{1/2} \cdot \left(\varepsilon_{y,n} \cdot \beta_y^*\right)^{1/2}}$$

Parameter	Units	Higgs	Top-high resolution	Top-high luminosity	Multi-TeV		
CoM energy	TeV	0.126	0.35	0.35	1.5	3.0	6.0*
Avg. luminosity	10^{34} cm^{-2}s^{-1}	0.008	0.07	0.6	1.25	4.4	12
Beam energy spread	%	0.004	0.01	0.1	0.1	0.1	0.1
Higgs production/10^7 sec		13,500	7000	60,000	37,500	200,000	820,000
Circumference	km	0.3	0.7	0.7	2.5	4.5	6
Ring depth [1]	m	135	135	135	135	135	540
No. of IPs		1	1	1	2	2	2
Repetition rate	Hz	15	15	15	15	12	6
$\beta^*_{x,y}$	cm	1.7	1.5	0.5	1 (0.5–2)	0.5 (0.3–3)	0.25
No. muons/bunch	10^{12}	4	4	3	2	2	2
Norm. trans. emittance, ε_T	π mm-rad	0.2	0.2	0.05	0.025	0.025	0.025
Norm. long. emittance, ε_L	π mm-rad	1.5	1.5	10	70	70	70
Bunch length, σ_s	cm	6.3	0.9	0.5	1	0.5	0.2
Proton driver power	MW	4	4	4	4	4	1.6
Wall plug power	MW	200	203	203	216	230	270

* Accounts for off-site neutrino radiation

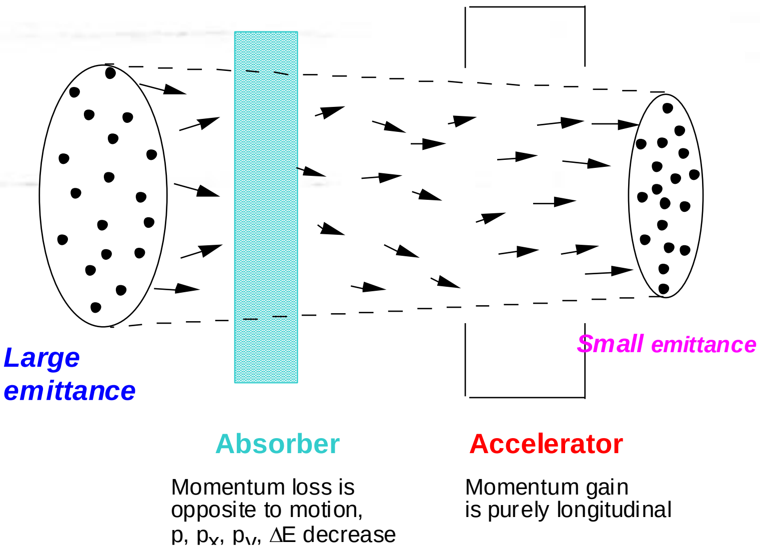
- Muon Collider will require cooling in 6D by 10^6

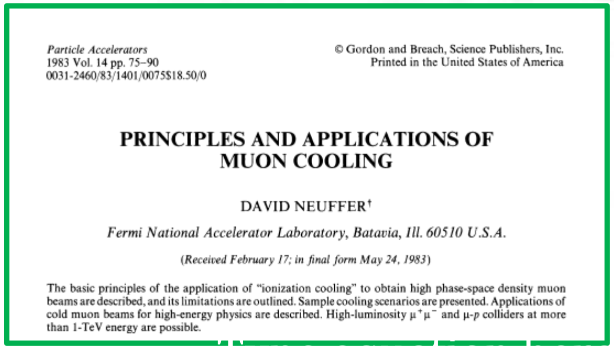
Cooling for a proton driven MC



- Front-end produces 21 well aligned muon bunches
- Two sets of 6D cooling schemes
  - One before bunch recombination and one after recombination
  - Combined they cool 6D emittance by 10^5
- Final cooling 4D
  - Additional cooling of the transv. emittance by an order of magnitude

Ionization cooling - transverse





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PRINCIPLES AND APPLICATIONS OF MUON COOLING

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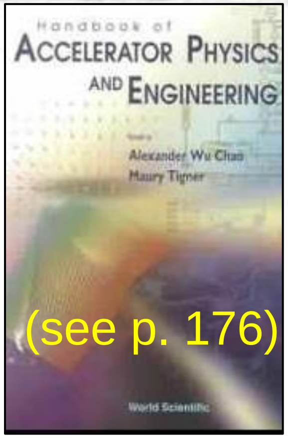
The basic principles of the application of "ionization cooling" to obtain high phase-space density muon beams are described, and its limitations are outlined. Sample cooling scenarios are presented. Applications of cold muon beams for high-energy physics are described. High-luminosity $\mu^+\mu^-$ and μ-p colliders at more than 1-TeV energy are possible.



Energy loss term

Multiple scattering term

$$\frac{d\varepsilon_T}{ds} = -\frac{1}{\beta^2 E}\frac{dE}{ds}\varepsilon_T + \frac{\beta\gamma\beta_T}{2}\frac{d\theta_0^2}{ds}$$

- Transverse cooling:
- Minimum emittance:

$$\varepsilon_T^{\mathrm{eq}} = \left(\frac{dE}{ds}\right)^{-1}\frac{\beta_T(13.6\ \mathrm{MeV})^2}{2\beta m_\mu c^2 L_R}$$

L_R: Radiation length

E: Muon energy

β_T: Transverse beta function

$\frac{dE}{ds}$: Energy loss

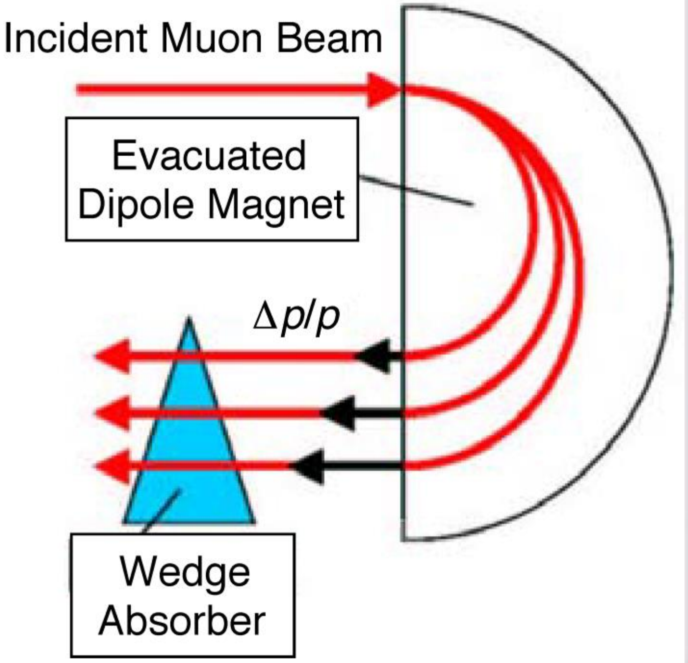
- Cooling can be controlled by material and magnetic focusing properties

Ionization cooling - longitudinal

Cooling term

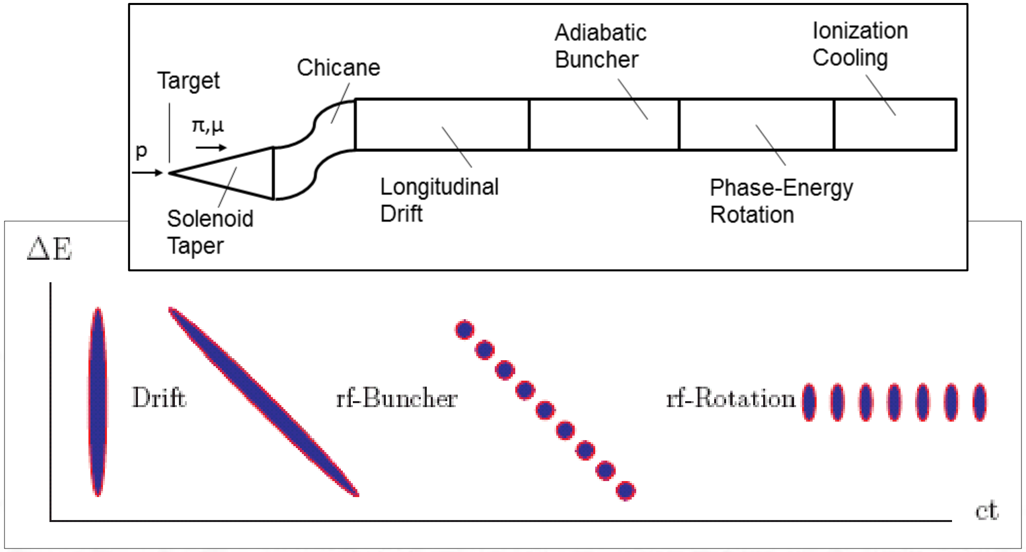
Straggling term

- Longitudinal cooling: $$\frac{d\sigma_E^2}{ds} = -2\frac{\partial\left(\frac{dE}{ds}\right)}{\partial E}\sigma_E^2 + \frac{d < \Delta E_{rms}^2 >}{ds}$$
- Cooling occurs only if derivative: $\frac{\partial\left(\frac{dE}{ds}\right)}{\partial E} > 0$
- Ionization loss does not naturally provide adequate longitudinal cooling
- Can be enhanced, if it is arranged that high energy muons lose more energy than low energy ones.



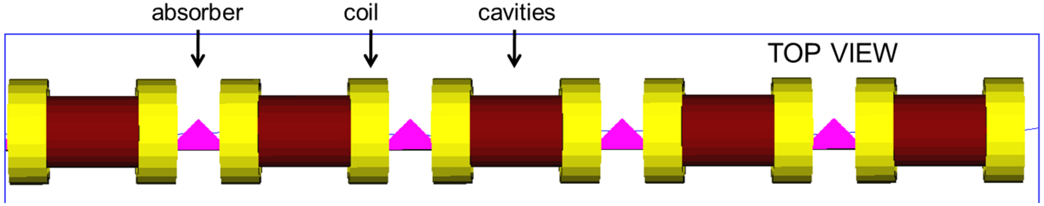
Beam pre-cooling preparation

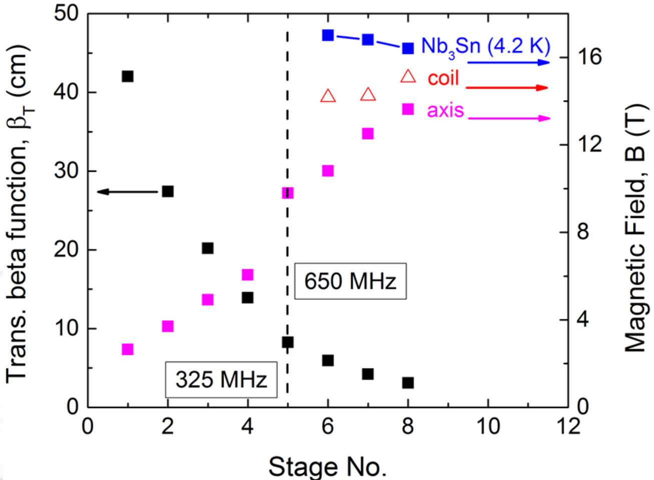
- Muons are born with large ΔE and small Δt
  - Front-end manipulates the beam from the target so that to create 21 well-aligned bunches
- Use a sequence ~120 rf cavities starting from 490 MHz and decreasing to 325 MHz
  - Can handle muons of both signs simultaneously

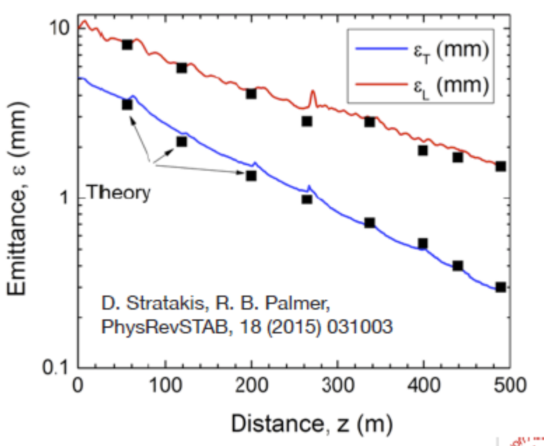


6D cooling based on vacuum rf cavities

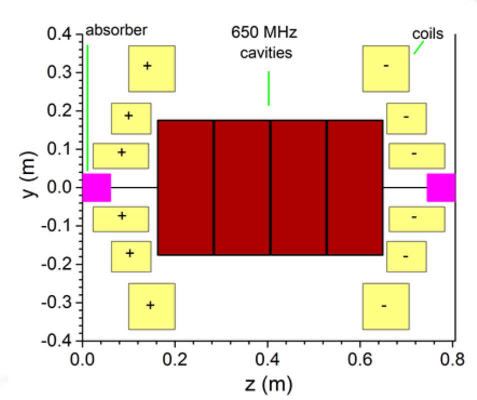
- One of the two options considered by MAP was a rectilinear channel with vacuum normal conducting rf cavities
- Showed cooling in 6D by 10^5
- Contains 8 stages with a total length of ~480 m





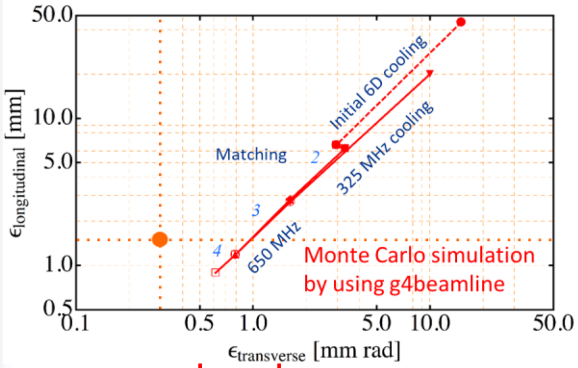


One cell

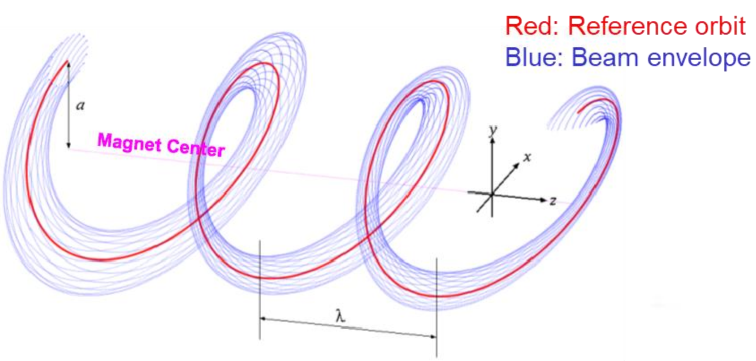


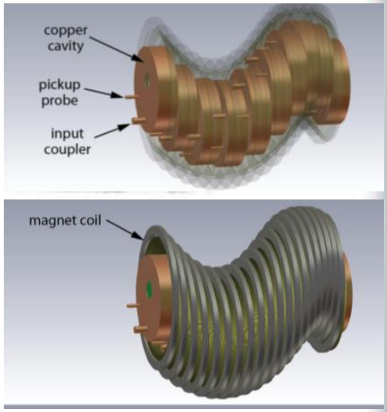
6D cooling based on gas rf cavities

- MAP also considered a helical cooling channel with hydrogen gas filled cavities
- It was composed of a solenoidal field with superimposed helical transverse dipole & quadrupole fields.
- Multi-staged system that also showed 10^5 cooling in 6D



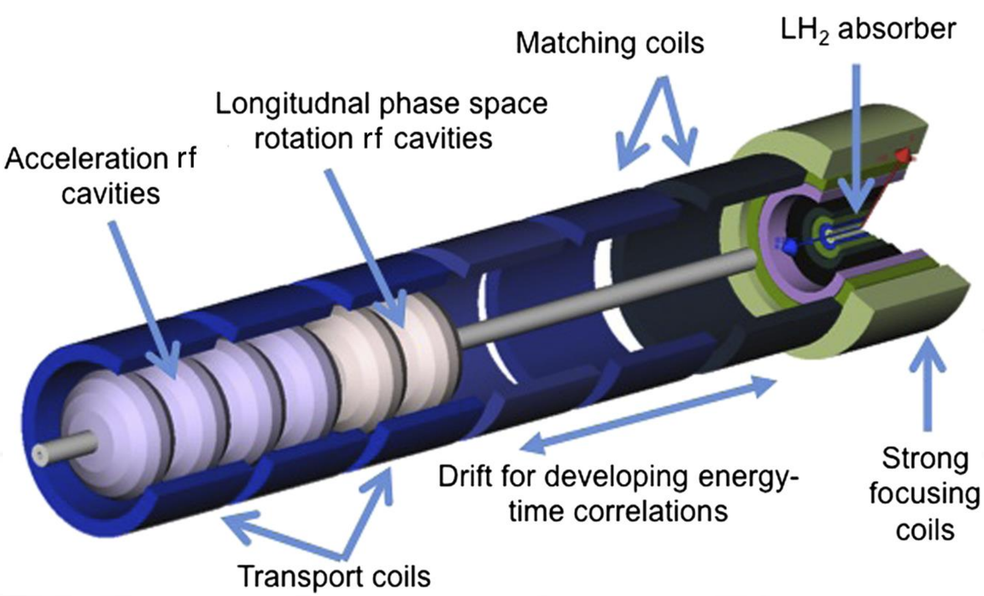
Seg.	λ	L	ν	B_z	b	b'	$\varepsilon_{T,eq}$	$\varepsilon_{L,eq}$	ε_{tr}
unit	m	m	MHz	T	T	T/m	mm rad	mm	
0							5.03	8.82	
1	1.0	50	325	4.41	1.32	−0.32	3.44	6.82	0.94
2	0.8	70.4	325	5.52	1.65	−0.50	1.62	2.41	0.90
3	0.5	120	650	8.83	2.63	−1.28	0.79	1.18	0.81
4	0.4	77.2	650	11.04	3.29	−2.01	0.61	0.89	0.85
		317.6							0.58

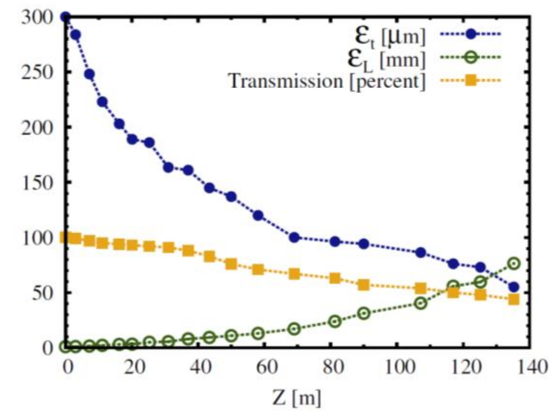


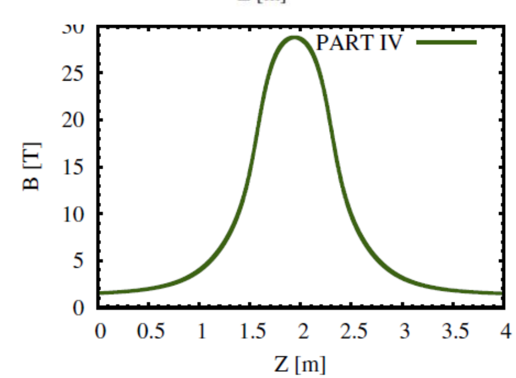


Final 4D cooling: High-field magnets

- Linear channel for additional 4D cooling with block absorbers
- Showed that 30 T magnets can reduce the 4D emittance by an additional order of magnitude -> As needed for a high luminosity multi-TeV collider



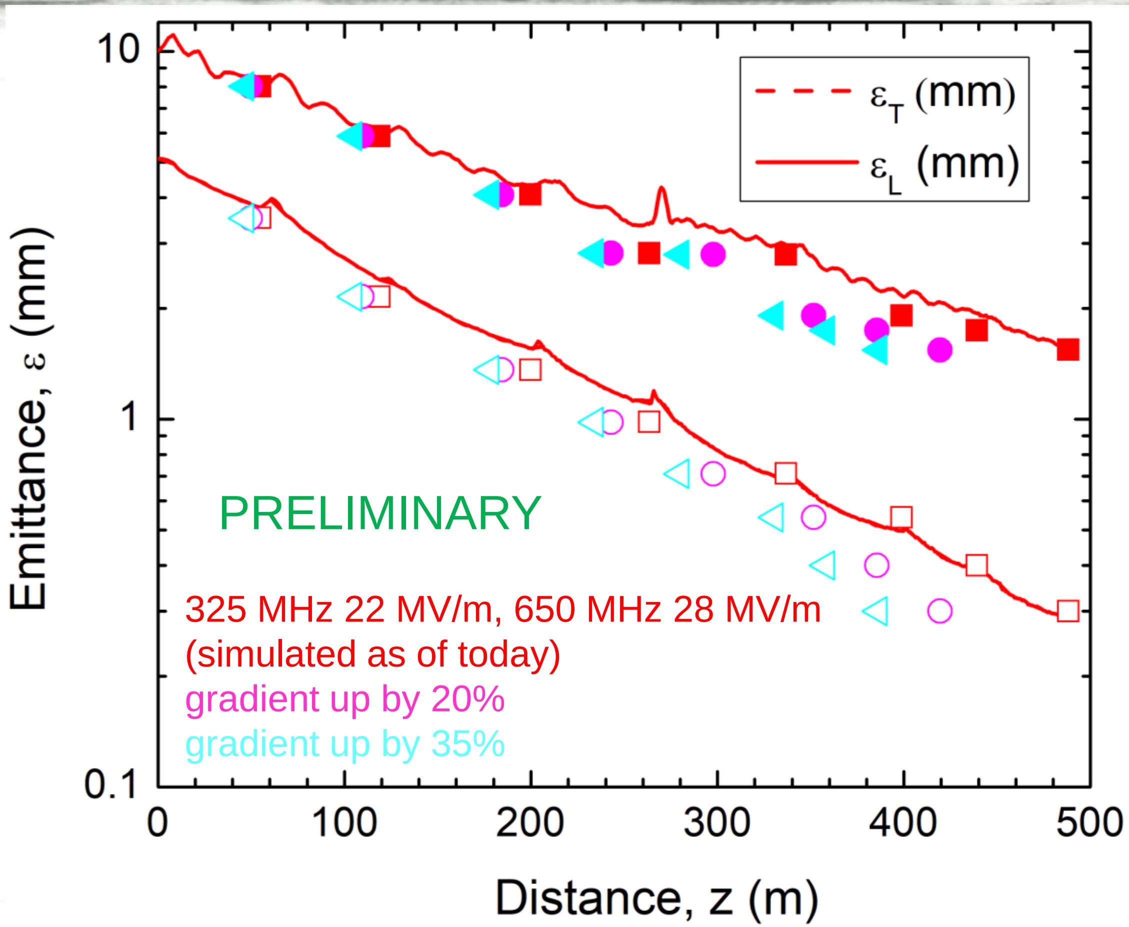




Comments

- 4D ionization cooling has been demonstrated by MICE and direct emittance exchange by the Fermilab Muon Campus
  - Moving from papers studies towards realization!
- Operation of rf cavities in B-fields has been demonstrated with both gas and vacuum rf cavities
  - Allows the use of higher rf gradients in our lattice designs
- Magnet technology progressed & 30+ T magnets are reality
  - Makes 6D cooling designs more flexible; currently considering only Nb_3Sn technology
- Advancement of optimization algorithms
  - Incorporation of these in lattice designs can make the channels more efficient

Future: Simulate with higher gradients



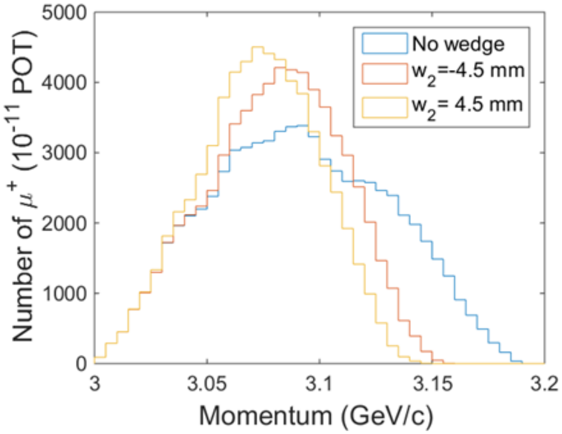
- Increasing the rf gradient can reduce the length of the cooling channel

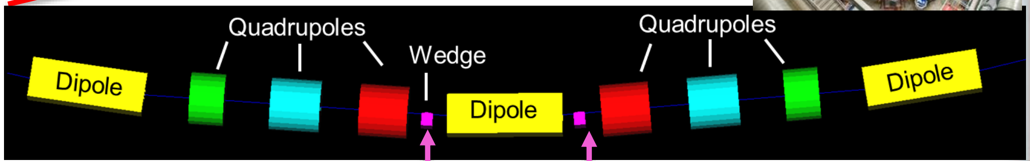
Summary

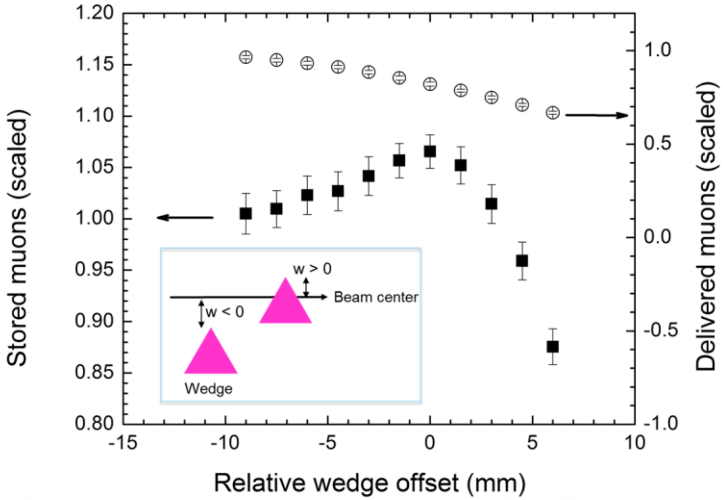
- Complete cooling schemes for a Muon Collider delivered by MAP with several technology options available
- They show promising transmission but more studies are needed especially towards the final cooling design
- Existing designs will benefit from:
  - Improvements of magnet technology
  - The demonstrated operation of NC rf in B-fields
  - The inclusion of advanced computational methods to improve efficiency
- Successful designs will require the corporation of rf, magnet and material experts

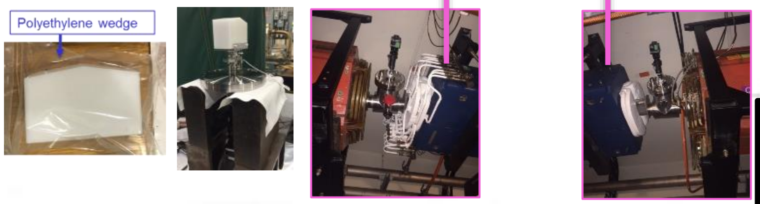
Demonstration of emittance exchange at the Fermilab Muon Campus

- Proof-of-principle experiment: Demonstrated 8% gain









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Application of passive wedge absorbers for improving the performance of precision-science experiments

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